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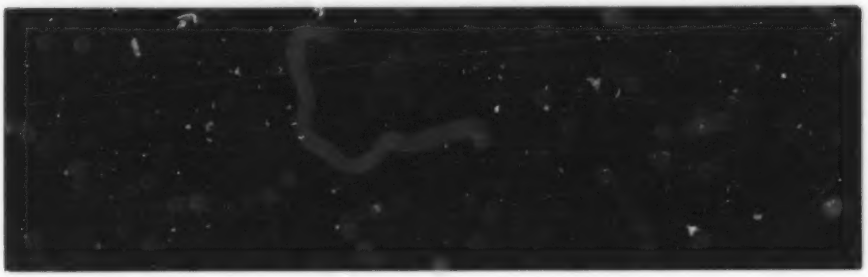

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STRESS CORROSION CRACK GROWTH RATES IN GAS PIPELINES - PROGRESS REPORT I

O. VOSIKOVSKY, F.A. MACLEOD AND D.R. KIFF

MTL 90-18(TR)

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REPORT MTL 90-18(TR)

STRESS CORROSION CRACK GROWTH RATES IN GAS PIPELINES
PROGRESS REPORT I

by

O. Vosikovsky, F.A. MacLeod and D.R. Kiff

SUMMARY

A stress corrosion cracking (SCC) experiment on a full size line pipe, designed to determine SC crack growth rates applicable for field conditions, is described in this report.

The 20-in. diameter pipe will be pressurized by a pressure sequence simulating one year of operation of a gas pipeline.

Ten environmental chambers, four with aqueous electrolytes simulating solutions found under disbonded coating, and six with soil and bacteria from pipeline sites where SCC was found will be placed on the pipe. Fifty six local environmental conditions will be created in the chambers by combining environment, cathodic protection potential, water table level in soil, and simulated disbonded coating.

Two surface cracks, 1.5 and 2.3 mm deep will be introduced for each condition. The growth of these cracks will be measured by the DC potential drop technique. Relevant environmental variables, and characteristics of bacteria will be monitored during the test.

LABORATOIRES DE LA TECHNOLOGIE DES MÉTAUX
RAPPORT MTL 90-18(TR)

VITESSE DE CROISSANCE DES FISSURES DE CORROSION SOUS CONTRAINTE DANS LES GAZODUCS: RAPPORT PROVISOIRE I

par

O. Vosikovsky, F.A. MacLeod et D.R. Kiff

SOMMAIRE

Une expérience de fissuration par corrosion sous contrainte (FCC) dans une conduite pleine grandeur, visant à déterminer la vitesse de croissance des fissures de CC dans des conditions d'utilisation, est décrite dans le présent rapport.

La conduite de 20 po de diamétre sera mise sous pression selon une séquence simulant l'utilisation d'un gazoduc pendant une année.

Le gazoduc sera examiné dans dix chambres environnementales, dont quatre contiennent des électrolytes aqueux simulant des solutions observées en présence d'un revêtement décollé de la paroi et six contiennent du sol et des bactéries provenant de sites de gazoducs où de la FCC a été observée. Cinquante-six conditions environnementales locales seront créées dans les chambres en combinant les paramètres suivants: environnement, potentiel de protection cathodique, niveau de la nappe aquatique dans le sol et revêtement décollé simulé.

Deux fissures de surface, de 1,5 et de 2,3 mm de profondeur, seront introduites dans chaque condition. La croissance de ces fissures sera mesurée par la technique de la chute de potentiel c.c. Les variables environnementales pertinentes et les caractéristiques des bactéries seront contrôlées pendant l'essai.

INTRODUCTION

Stress corrosion cracking (SCC) has been observed recently in many locations on natural gas pipelines operated by TransCanada PipeLines (TCPL) and NOVA. The TCPL lines have experienced several service failures from growing SC cracks. The field investigations have shown that SCC occurs under disbonded coatings. Colonies of axially-oriented, densely-spaced cracks initiate on the pipe surface. As these cracks grow they coalesce into longer cracks, and eventually penetrate the pipe wall leading to a leak or rupture.

The electrolyte trapped under the disbonded coating over the cracks (termed non-classical) is relatively dilute, with pH near neutral. This makes it basically different from the classical, concentrated carbonate-bicarbonate solution, with pH between 9 and 10, identified by American Gas Association as responsible for SCC in gas pipelines.

Since the SCC in Canadian gas pipelines appears to be widely spread, there is an immediate need to establish effective inspection schedules and procedures to avoid further service failures. To this end, a knowledge of SC crack growth rates under field conditions is essential. To date, research sponsored by TCPL (1-6), has been only marginally successful in growing cracks in the non-classical electrolyte. No growth rates for deeper cracks, needed for establishing inspection intervals, have been so far measured.

The principal aim of the present joint research project with NOVA, TCPL, University of Waterloo, and NOVA/Husky Research Corporation (NHRC), is the determination of growth rates of intermediate or larger SC cracks under simulated field conditions. The research at MTL involves long-term (one-year) testing of a linepipe, pressurized by a simulated gas pipeline spectrum, with a variety of artificial and natural cracks, under a variety of environmental conditions, including soils with bacteria. The research at the University of Waterloo is focussed on measuring crack growth rates in small edge-cracked laboratory specimens loaded by static load with a small constant amplitude cyclic component. The NHRC research will examine the role of soil and bacteria in SCC. Certain environmental conditions will be used in each project to make possible correlation of the results. NOVA and TCPL are conducting extensive field investigations of conditions leading to SCC (7-9).

This report describes the MTL pipe test, namely, the design of pressurization and DC potential drop (DCPD) crack growth data acquisition systems, the design of environmental chambers and the monitoring of environmental variables, and the test matrix. An exhaustive literature review on non-classical SCC has been presented in the University of Waterloo progress report (1). Here only brief rationale for selection of test parameters will be given in conjunction with the test matrix.

TEST PIPE, LOADING, AND INITIAL CRACKS

The primary criterion for selection of test design and test conditions was to simulate field conditions as closely as possible to ensure that the measured crack growth rates are representative of actual pipeline operation. Thus, the full-size pipe section, excavated from the NOVA Valleyview Lateral Pipeline after seventeen years of service with naturally grown SCC colonies, will be used as the test pipe. During the one-year test, the test pipe will be loaded in real time (1 cycle/day) by a pressure sequence representing one-year service (preceding to SCC failure) of TCPL Line 100-2.

The 508 mm (20 in.) O.D., 4.5 m long test pipe, with 6.4 mm thick wall, made of X65 (Grade 448) steel is shown in Fig. 1. The MTD Eng. computer controlled pressurizing, and DCPD data acquisition systems for application of the pressure sequence, and crack growth monitoring are seen in this figure. The pipe is not yet instrumented for DCPD measurements, and the environmental cells are not in place.

The one-year pressure sequence of peaks and valleys, shown in Fig. 2, contains 310 cycles with the majority of the peaks near the maximum operational pressure (MOP) of 6950 kPa, and the deepest valley at 5050 kPa. The pressure fluctuations are rather small, the most common range is 150 kPa, the largest range is 1500 kPa (21% of MOP). Details on the pressure sequence are given in the MTL Report (10), appended to this report. During the test the sequence will be exactly replicated at the frequency of 1 cycle/28.3 h, using a sinusoidal load wave.

The hydraulic system includes a safety circuit consisting of an electrically controlled shut-off valve and a large accumulator which in case of power failure locks pressure in the pipe until the system is restarted. Thus, unwanted large pressure drops likely to be generated by power or control system failures during the one year period are avoided.

Ten environmental chambers, four with aqueous environments and six with soil and bacteria, will be placed on the test pipe. Local environmental conditions in the chambers will be varied by positioning the initial cracks either on the open pipe surface or under simulated disbonded coating. In the chambers with soil, the additional variable will be the position of the cracks along the pipe circumference in conjunction with variable cathodic protection and water table levels. In total, 56 different environmental enclaves will be created. The environmental conditions will be described in the section dealing with the test matrix.

A set of two initial, nearly semi-elliptical, surface cracks will be used in each enclave. The dimensions and spacing of the cracks are given in Fig. 3. The cracks will be cut by 0.1-0.15 mm thick slitting saws. The maximum crack depth, a, of 1.5 and 2.3 mm corresponds to a wall penetration, a/t, of 23 and 36%, respectively. Aspect ratios a/c of both cracks are equal to 0.19. Stress intensity factors, K, at MOP are 20.1 and 25.4 MPa$\sqrt{m}$, respectively.

The depth growth of these cracks will be monitored by the DCPD technique, using a 128-channel system recently developed by MDT Eng. A similar system is being used by the University of Waterloo (1).

Four wire probes, straddling each crack will be spot welded onto the pipe surface as shown in Fig. 3. The outside pair of probes will introduce DC current, which will create a potential field across the crack. Change in the potential field associated with crack growth will be monitored by the inside pair of potential probes. Calibration of the system will be done on a spare pipe by cutting and monitoring progressively deeper saw slits. For final, post mortem calibration, initial and final crack depths measured on sectioned surfaces will be used.

In each of the six environmental chambers with soil and bacteria, in addition to artificial deep cracks, a colony of natural SC cracks, grown during pipeline service, will be exposed to the environment. An example of a small colony is shown in Fig. 4. The number of cracks and crack length distributions will be measured before and after the test using an image analyzer. These measurements should provide valuable information on surface growth and coalescence of SC cracks.

ENVIRONMENTAL CHAMBERS, MONITORING OF ENVIRONMENTAL VARIABLES

Two types of environmental chambers will be used. For aqueous environments the chamber, as shown in Fig. 5, is a simple acrylic 9-in. O.D. tube, shaped at the bottom to fit the pipe surface. It will be sealed and strapped on top of the test pipe. Capillaries, counter electrodes, and inlets and outlets for the gas will be inserted through the lid sealed on top of the tube.

The double chamber for soil, shown in Fig. 6, will encompass the pipe, providing a soil layer which will be 140 mm thick at the bottom and 250 mm thick at the top. To accommodate the distribution of crack colonies on the test pipe, each box is partitioned in the middle, thus creating two chambers. A horizontal split in the middle with flanges makes installation and sealing of the chambers on the pipe possible. Each double chamber will contain about 0.2 m^3 of soil.

Environmental variables will be monitored at locations of every set of cracks. Electrochemical potential on the pipe surface will be measured using Luggin capillaries placed between the cracks. In the case of cracks under simulated disbonded coatings the capillary will be sealed under the tape.

Another set of capillaries will be installed to periodically extract samples of electrolyte for pH measurements and identification of bacteria. To avoid disturbing the solution over the cracks, a dummy disbonded tape will be installed next to the crack locations for electrolyte extraction.

Soil samples will also be periodically removed for bacterial analysis. Different metabolic groups will be enumerated using enrichment media. The metabolic groups will include sulphate-reducing bacteria, ammonia producers, and ammonia and nitrite oxidizing bacteria. The total acid

producers and the total heterotrophs will also be counted. As a general indication of bacterial activity the production of CO_2, H_2, and CH_4 by soil and fluid samples will be measured using gas chromatography. Levels of hydrogenase concentration will provide a general indication of bacterial corrosion activity. The production of organic acids which can also be corrosive, will be measured by high-pressure liquid chromatography. Various ions present in the liquid soil phase and in the fluid under the disbondments will be measured using ion chromatography and atomic adsorption. The pH of these samples will also be measured. The water content and redox potential of the soil will be measured with time domain reflectometry and wax impregnated graphite electrodes, respectively.

TEST MATRIX

The objective of the pipe test is to determine SC crack growth rates under conditions which represent the actual gas pipeline operation as closely as possible. To this end a full size line pipe has been chosen as a test piece, and it is to be tested under the following conditions.

The test pipe was excavated from a seventeen year old pipeline experiencing SCC. Six SCC colonies which had grown during pipeline service were detected on the pipe, and their growth will be measured. However, of primary interest is the growth rate of large cracks in the wall thickness direction. For each environmental condition two semi-elliptical cracks 1.5 and 2.3 mm deep will be introduced and their growth monitored by the DCPD technique.

The test pipe will be loaded with a one year gas pipeline pressure sequence in real time, exactly reproducing the field loading (10).

The test will be conducted at ambient (20-25°C) temperature. The previous field and laboratory investigations did not show any dependence of non-classical SCC on temperature (1,3,7-9).

Ten environmental chambers, four with aqueous solutions and six with soil and bacteria, will be mounted on the test pipe. The layout of the chambers on the pipe is shown in Fig. 7. The test and environmental conditions in single chambers are summarized in Table 1.

In selecting environmental parameters, three basic criteria were used:

simulation of field conditions
propensity to produce SCC
correlation with current and past tests

Field investigations (7,8) have shown that dilute electrolyte with a pH between 6 and 7 is always associated with SCC in Canadian pipelines. Laboratory attempts to reproduce field SCC (2-5) indicated that, particularly under cathodic protection, a CO_2 presence in the solution is required to keep the pH below the neutral level. Carbon dioxide kept the pH level low even in a crevice simulating disbonded coating with holidays at relatively high cathodic protection. Parkins

(4,5) concluded that the SCC is likely associated with hydrogen embrittlement, and thus, will be exacerbated at lower cathodic potentials if low pH is maintained. In the field, it is expected that carbon dioxide will be produced by soil bacteria, but it is not known whether sufficient quantities are produced to buffer the low pH (2).

Considering this, and the fact that pipelines are almost always cathodically protected, two cathodic potentials, near optimum protection (-0.8 V), and slight overprotection (-1.1 V vs. SCE) will be used in addition to free corrosion conditions in the environmental cells. A potentiostat will be used for optimum protection. Sacrificial pure zinc anodes connected to environmental chambers by salt bridges will be used for cathodic overprotection. In the case of soil-filled chambers, only one anode will be used, with the salt bridge located at the 9 o'clock position. This arrangement is expected to provide variable cathodic protection around the pipe circumference, maximum at 9 o'clock, minimum at 3 o'clock, and intermediate at 12 and 6 o'clock locations of the cracks.

SCC in pipelines is always found under disbonded coating. Thus, a disbonded tape will be simulated over one set of two cracks, as shown in Fig. 3. The tape will contain two holidays, one above the centre of each crack. In order to correlate results with laboratory tests, usually done without coating, an extra set of cracks on open, uncoated pipe surface is added next to each set of cracks under disbonded tape, as shown in Fig. 7. Simulated disbonded coating will be provided over all natural SCC colonies.

In three of four environmental chambers the NS4 electrolyte, representative of solutions found above SCC colonies in the field (7-9), will be used. In the first cell, the classical concentrated carbonate/bicarbonate electrolyte (AGA solution), will be used as a reference.

The remaining six chambers will contain two soil types that will be obtained from pipeline areas that have experienced SCC. If bacteria play an important role in the development of SCC, these soils should contain microbial flora which is very conducive to the development of SCC. It is tentatively planned that Nova will provide a clay-based soil while TCPL will provide a sandy loam type. The two soils will possess different water retention characteristics. This will permit the examination of different drainage profiles.

Time domain reflectometry measurements will indicate whether there is a correlation between the soil water content and SCC, similar to that reported with water content and pitting corrosion (11). Furthermore, the water table in the environmental cells will be varied where possible since there is some evidence that a fluctuating water table and imperfect drainage is correlated with the development of SCC in Northern Ontario (12).

Two of the chambers containing soils will also contain a layer of soil mixed with FeS. Iron sulphide is often formed when H_2S produced by sulphate-reducing bacteria reacts with soluble iron. The addition of FeS to the environmental cells will serve to accelerate this natural process. The influence of FeS on SCC will be investigated, since it has been reported that iron sulphide and aerated water will form polythionic acids, which will induce the cracking of sensitized austenitic

stainless steel (13). In an effort to prevent the FeS from forming an electric circuit with the pipe and acting as a cathodic depolarizer, the FeS-containing layer will be separated from the pipe by an additional soil layer (Fig. 7). However, with time it is possible that the FeS will move downwards in the soil and make contact with the pipe. The aerated water will be provided by the periodic addition of artificial rainwater (distilled water) to the soil surface.

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Table 1. Test matrix.

<table>
<tr><td>CELL NO.</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td></tr>
<tr><td>Loading</td><td colspan="10">One year pressure sequence derived from TCPL line, applied in real time.</td></tr>
<tr><td>Initial Defects</td><td colspan="4">Two sets of two semi-elliptical slits, 1.5 and 2.3 mm deep in each set. One set under simulated disbonded coating, one on open surface, as shown in Fig. 3.</td><td colspan="6">Eight sets of two semi-elliptical slits (1.5 and 2.3 mm deep) at the 3, 6, 9 and 12 o'clock positions as shown in Fig. 7. At each of these four positions one set will be under simulated disbonded coating and one set will be on open surface.

A colony of natural cracks near 3 o'clock position under simulated disbonded coating.</td></tr>
<tr><td>Crack growth monitoring</td><td colspan="4">DC potential technique for artificial cracks (slits). One probe at the center of each slit.</td><td colspan="6">Surface length and distribution of natural cracks measured before and after the test.</td></tr>
<tr><td>Environment</td><td>AGA solution</td><td colspan="3">NS4 solution saturated with CO_2</td><td colspan="6">Soil + Bacteria</td></tr>
<tr><td></td><td></td><td colspan="3"></td><td>TCPL Soil</td><td>NOVA Soil</td><td>TCPL Soil</td><td>NOVA Soil</td><td>NOVA Soil</td><td>TCPL Soil</td></tr>
<tr><td></td><td></td><td colspan="3"></td><td colspan="4">Variable water table from top of soil to mid-height of the pipe.</td><td colspan="2">FeS added
Variable water table with FeS in top soil layer as shown in Fig. 7</td></tr>
<tr><td>Potential (vs SCE)</td><td>F.C.</td><td>F.C.</td><td>-0.8V</td><td>-1.1V</td><td>F.C.</td><td colspan="5">-1.1V applied through salt bridge at 9 0'clock position (Fig. 7)</td></tr>
</table>

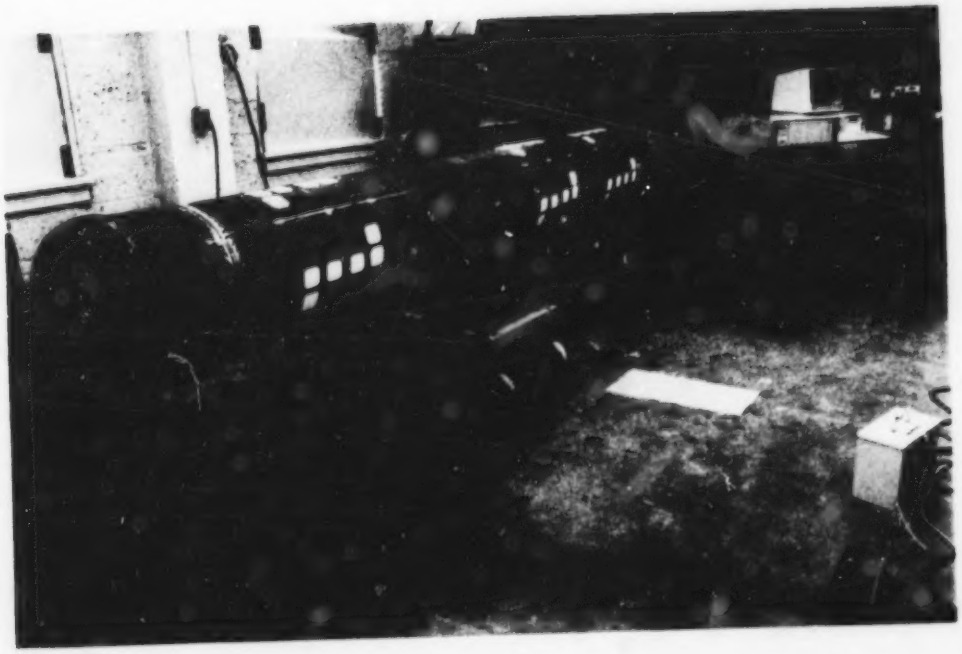

Fig. 1. The test pipe with pressure supply, pressure control and data acquisition systems. (neg 20002-5)

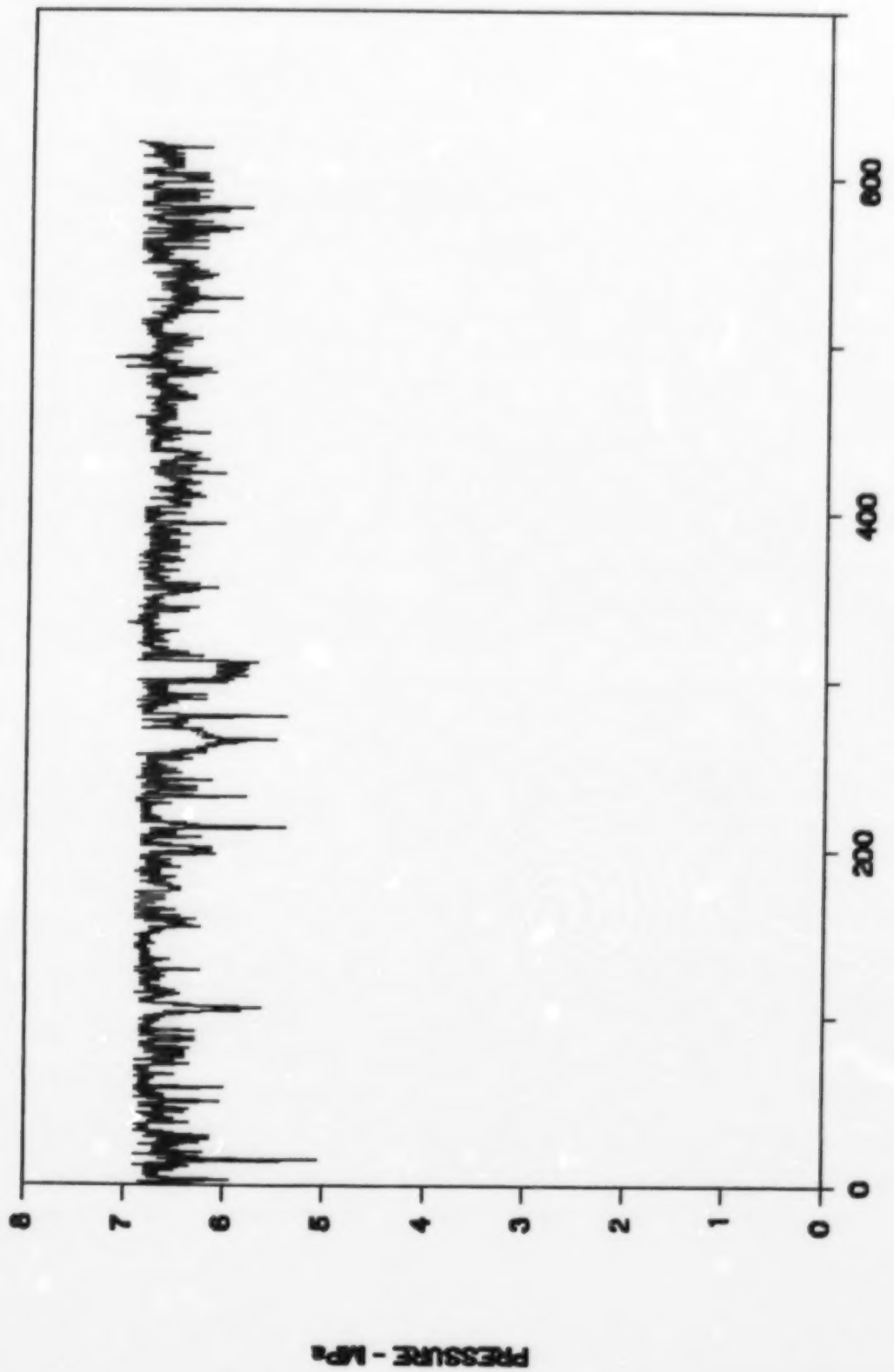

Fig. 2. One-year pressure history of a gas pipeline.

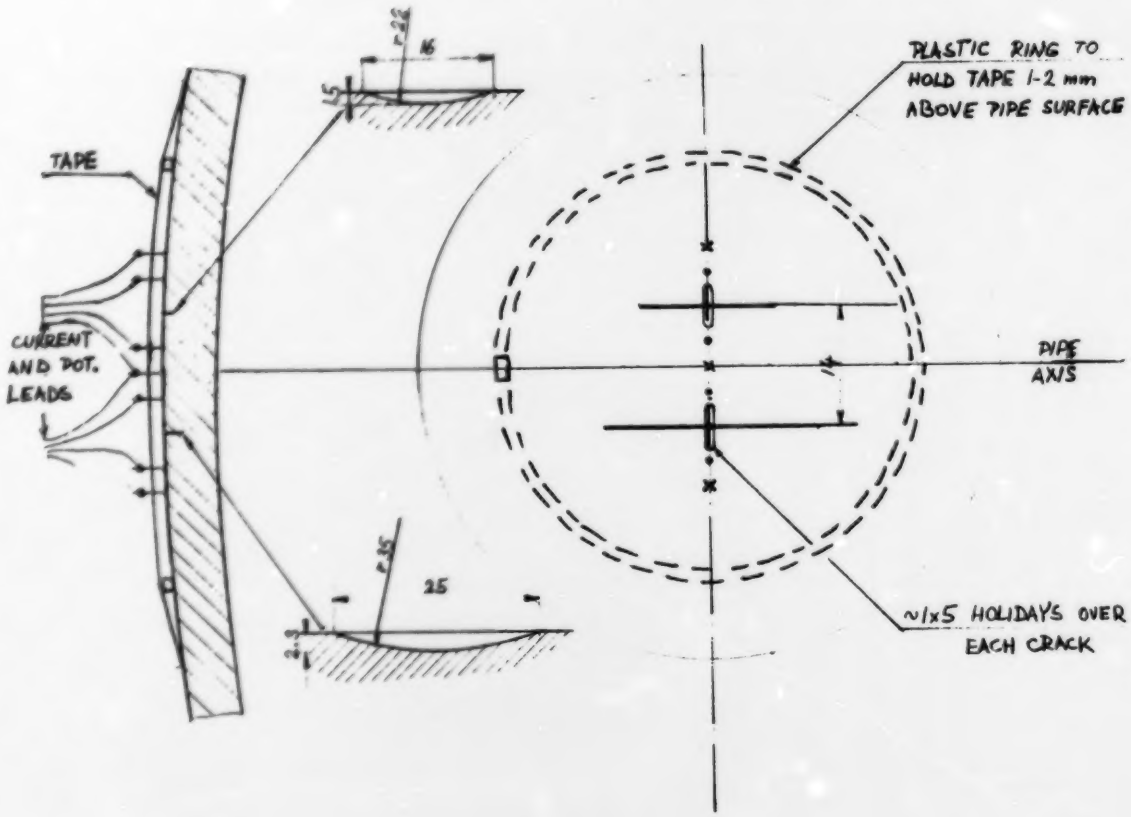

Fig. 3. Layout and size of initial cracks, DCPD probes, and simulated disbonded coating in a set of cracks.

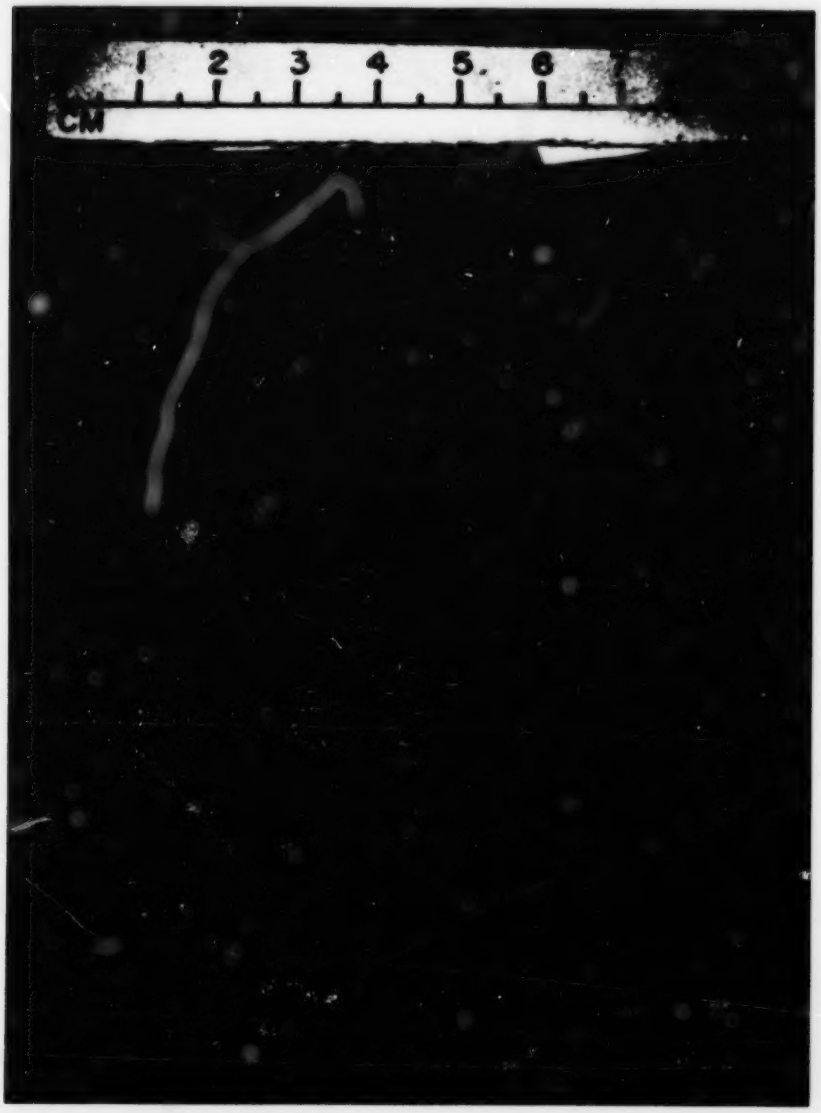

Fig. 4. Example of a relatively small SCC colony revealed by magnetic particle inspection. (neg 20002-14)

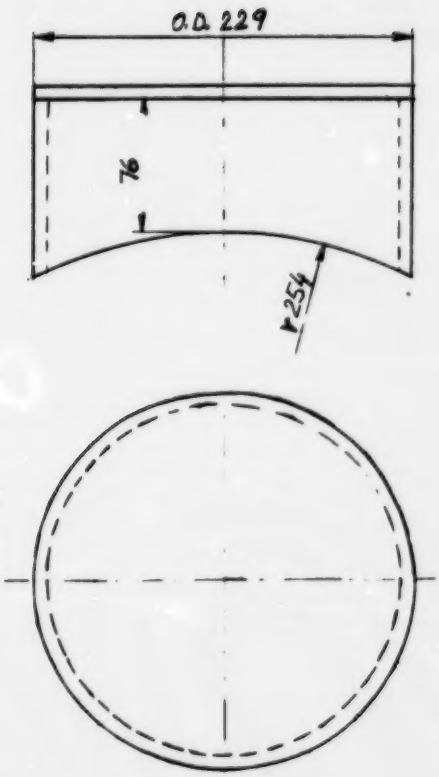

Fig. 5. Environmental chamber for aqueous environments.

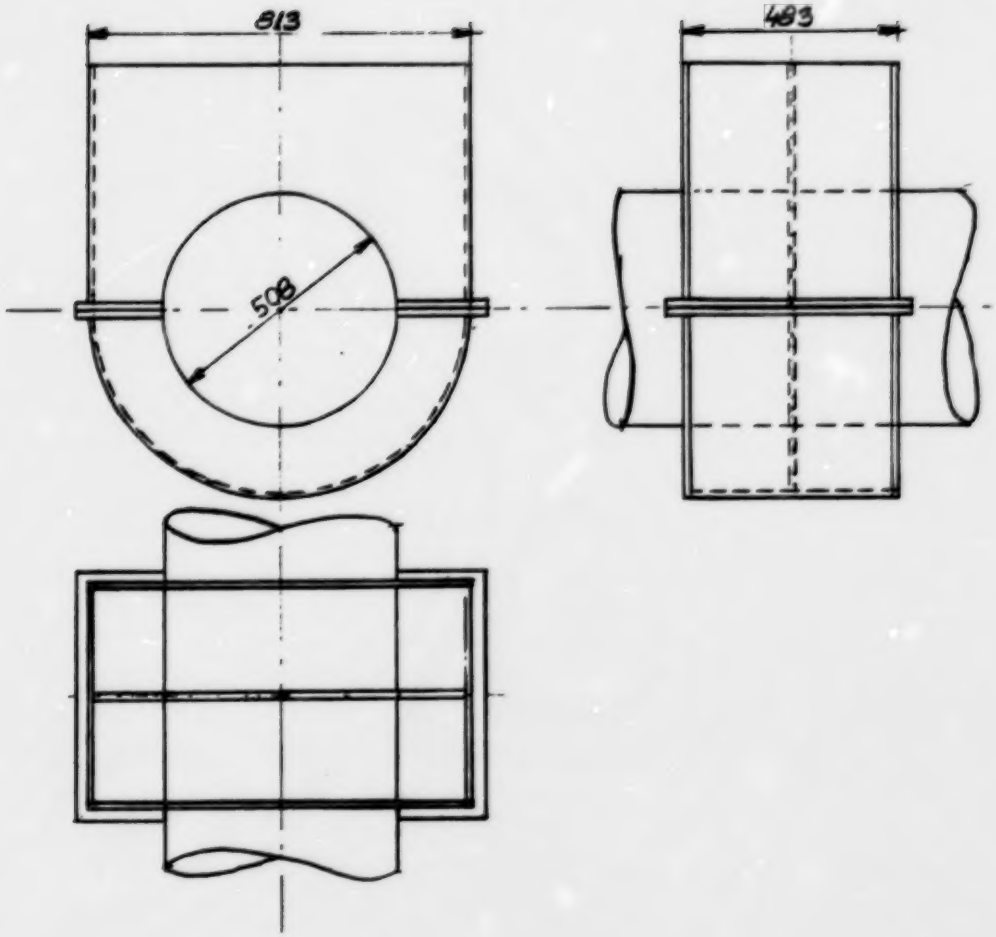

Fig. 6. Environmental double chamber for soil and bacteria.

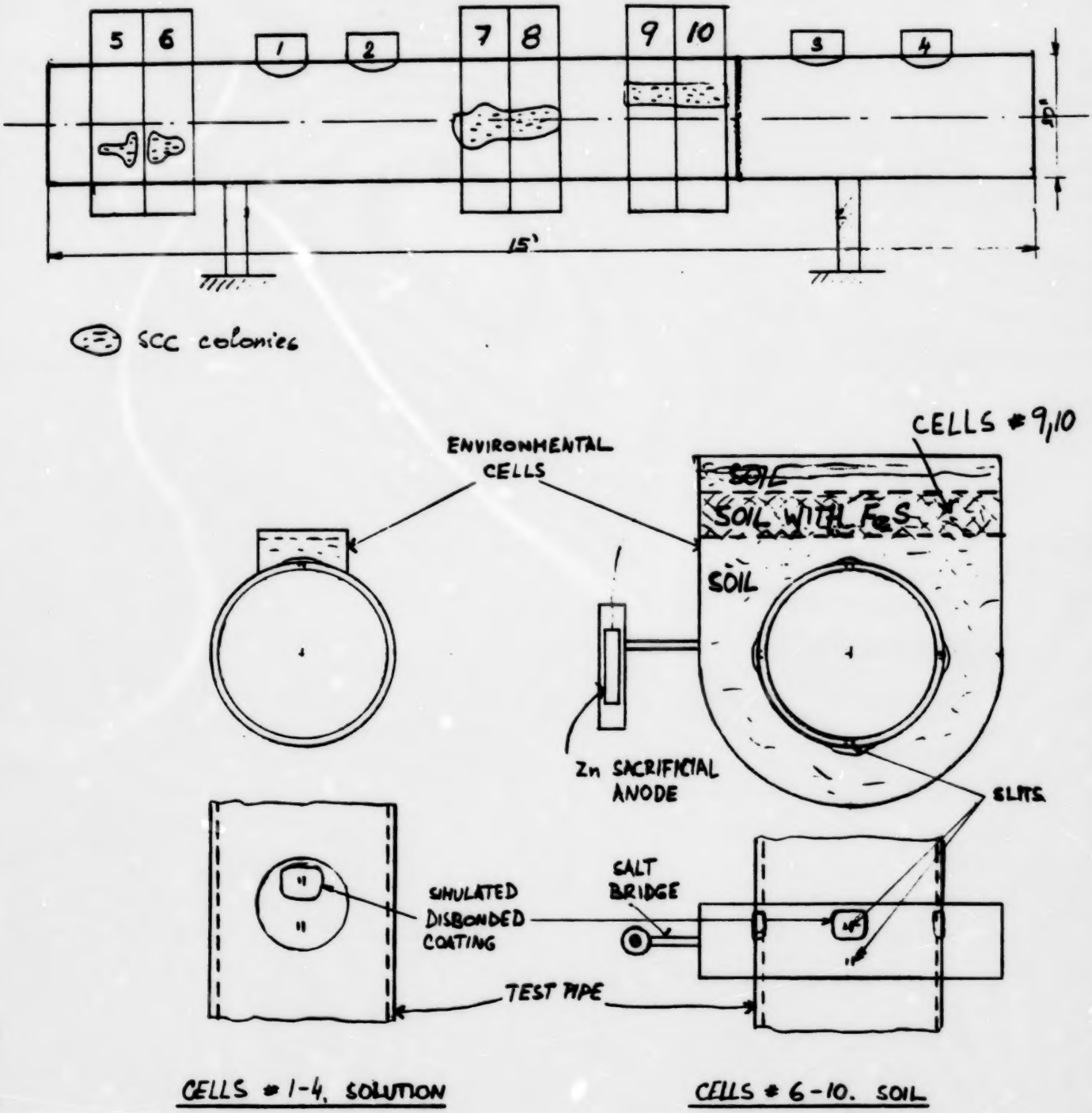

Fig. 7. Layout of environmental chambers, initial cracks, and disbonded coatings on the test pipe.